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Single-frequency tunable 447.3 nm laser by frequency doubling of tapered amplified diode laser at cesium D_1 line

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Abstract: A continuous single-frequency tunable blue laser at 447.3 nm is developed by external-cavity frequency doubling of a tapered amplifier-boosted continuous-wave diode laser at cesium (Cs) D_1 line. A maximum blue power of 178 mW with 50.8% conversion efficiency is obtained. It can be continuously tuned over a range around 1.6 GHz as the diode laser frequency is scanned across the $F = 4 \rightarrow F' = 3$ transition of ^{133}Cs D_1 line. The generated tunable and stable blue laser source has potential applications in constructing quantum light-atom interfaces in quantum networks.

OCIS codes: (190.2620) Harmonic generation and mixing; (140.4780) Optical resonators.

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1. Introduction

Single-frequency tunable lasers are key resources for the applications of optical spectroscopy, metrology, recording, atom manipulation, and quantum networks due to their continuous frequency sweeping across the range of interest [1–3]. By using frequency doubling, the tunable laser at shorter visible wavelength can be obtained for special atomic excitations, e.g., 532 nm laser for Iodine (${}^{127}I_2$) hyperfine luminescence [4], 656 nm laser at the radiative transition ${}^2S_{1/2} \leftrightarrow {}^2D_{5/2}$ of Silver (Ag) atoms [5], 671 nm lasers scanned across the absorption spectrum of $2^2S_{1/2} \leftrightarrow 2^2P_{1/2,3/2}$ on D_1 and D_2 lines of Lithium (Li) atoms [6,7], and 399nm laser for the ${}^1S_0 \leftrightarrow {}^1P_1$ excitation of Ytterbium (Yb) atoms [8]. Furthermore, by using two frequency doubling processes, the ultraviolet laser sources for $5s^2\,{}^1S_0 \rightarrow 5s5p\,{}^3P_1$

intercombination line at 230.6 nm and $5s^2\,{}^1S_0 \rightarrow 5s5p\,{}^3P_0$ of In^+ transition at 236.5 nm can also be achieved [9].

On the other hand, frequency doubling has been widely used to produce a pump beam for parametric down conversion process with non-classical light generation [10,11], which has become a major ingredient in quantum networks for large-scale quantum information process [12]. Such a network consists of quantum nodes of matter (e.g., atoms) and interconnecting channels of light (e.g., non-classical light) [13] for transmitting information between spatially remote nodes. Hence, the atom-light interface with alkali atoms and non-classical light is the key part of quantum networks, in which the laser frequency needs to be precisely tuned to match the atomic transition, e.g., the squeezed light locked at 852 nm of Cs D_2 line [14] or 795 nm of rubidium (Rb) D_1 line [15–17] via frequency doubling and parametric down conversion. These non-classical light resources have important applications in atomic spin squeezing [18], atomic entanglement generation [19], spectroscopy measurement [20] and quantum memory [21].

The Cs D_1 line at 894.6 nm has the advantage of simplified hyperfine structure for experimental realization of a light-atom interface, and it also lies well within the wavelength regime of excitonic transition in InAs/GaAs quantum dots for integrated quantum interfaces between light and solid-state systems [22]. For the purpose of preparation of tunable non-classical light at 894.6 nm of Cs D_1 line, a frequency tunable 447.3 nm laser is necessary as a pump beam for parametric down-conversion. Blue lasers at 447.3 nm were investigated by intra- and extra-cavity frequency doublings of Cs vapor laser with PPKTP, BiBO, and LBO crystals [23–25], of which a maximum power up to 1 W was obtained with a conversion efficiency of 14%. These systems were operated in the pulse mode with broader linewidth, which limits the potential applications in developing continuous-wave resources. Additionally, current commercial narrow-linewidth diode lasers can cover wide wavelength regions with precision frequency tunability of several GHz, however, they are limited by the output power of lower than 50 mW at blue wavelength. To get a higher power of blue laser for special atomic excitation or other applications, the frequency doubling of infrared diode laser was investigated, e.g. up to 100 mW 328 nm laser using frequency doubling of vertical external-cavity surface-emitting laser, corresponding to a low conversion efficiency of 1.5% due to the low beam quality of diode laser [26]. The high power blue laser source can also be commercially obtained using frequency doubling of comprised diode laser and semiconductor (TA) or fiber (FA) amplifier system, however, only 20% conversion efficiency at wavelength range of 350-450 nm is obtained [27]. Also the efficient frequency doubling of Ti:sapphire laser, which has broad achievable spectral range from 680 nm to 1070 nm [28], can provide more tunable blue or ultraviolet lasers e.g. at 423 nm [29], 378 nm [30] and 399 nm [8]. Although the extremely wide gain bandwidth (680–1070 nm) of Ti:sapphire crystal allows one to achieve desirable lasers within the 325–535 nm range, the actual attainable system with relative high power is located within the narrower range of 390–425 nm due to its efficient mode operation near 800 nm.

Alternatively, the high power and wide wavelength of 400 nm to 670nm laser resources can be generated via frequency doubling of high power wavelength-selectable tapered amplified diode laser systems [31,32]. In these high power frequency doubling systems, a bow-tie ring enhancement cavity was used to avoid spatial hole burning (may occured in the standing-wave cavity) and to circumvent thermal lensing effect, so that a stable high power output can be obtained [33–35].

In this paper, we investigate the tunable 447.3 nm blue laser via frequency doubling of a tapered amplifier (TA) boosted external-cavity diode laser (ECDL) system at 894.6 nm. In order to obtain tunable laser with efficient frequency doubling, we use a compact two-mirror standing-wave cavity with 10 mm long PPKTP crystal to reduce the number of elements [36]. Due to the low power operation of cavity, the spatial hole burning and thermal lensing effects has less influences on output. We also use the separate single-mode fibers to spatially filter the laser beam and TA amplified output beam. The transverse beam profile of laser pump system is successfully improved and thus a blue laser with good beam pfofile is obtained. As a result, 178 mW power with 50.8% high conversion at 447.3 nm is obtained with 350 mW mode-matched diode pump. The cavity is actively stabilized by using a frequency-modulation Pound–Drever–Hall (PDH) sideband locking technique, which enables the detection of the error signal at a high frequency where the error slope and signal-to-noise ratio is large, leading to a large acquisition range for robust lock [37]. We therefore show that the frequency of generated 447.3 nm laser can be continuously tuned about 1.6 GHz when the tuning range of diode laser covers the $F = 4(6^2S_{1/2}) \rightarrow F' = 3(6^2P_{1/2})$ transition of ^{133}Cs D_1 line. The root mean square (RMS) fluctuation of output power is measured to be less than 2.3% and 1% for different pump powers of 350 mW and 200 mW over 2 hours, respectively.

2. Experimental setup

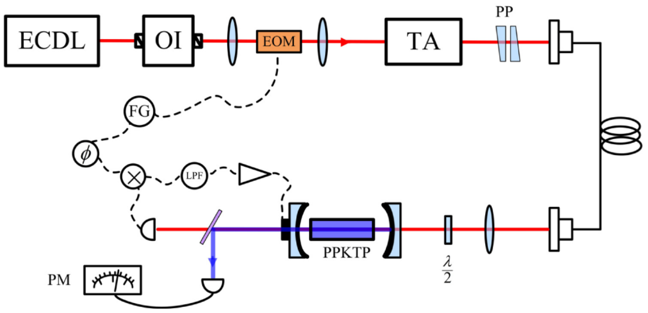

Fig. 1. Experimental setup. ECDL: external-cavity diode laser; OI: opitcal isolator; EOM: elecro-optic modulator; TA: tapered amplifier; APP: Anamorphic Prism Pairs; HWP: half-wave plate; MML: mode-matching lens; DBS: dichroic beam splitter; FG: function generator; LPF: low pass filter; PID: proportional-integral-derivative controller; PM: power meter.

The schematic of experimental setup is presented in Fig. 1. A continuous-wave ECDL with the center wavelength of 894.6 nm on the ^{133}Cs D_1 line is employed. The ECDL with about 15 GHz mode-hop free tuning range is locked to the Cs D_1 line using polarization spectrum, in which the ECDL frequency was not modulated to avoid the influence of the frequency doubling cavity. It has the maximum power of 50 mW and linewidth of 1 MHz, and acts as a seed laser to inject into a tapered amplifier (TA) to get 500 mW high power laser source, which is used to pump a PPKTP crystal in standing-wave structure formed by two curved mirrors with radius of curvature of 30 mm (input coupler) and 50 mm (output coupler) for frequency doubling. The input coupler is highly reflecting at 447.3 nm, and has a transmissivity of 5% at 894.6 nm, while the output coupler mounted on a piezo-electric transducer (PZT) is highly reflecting at 894.6 nm and has a transmissivity of 95% at 447.3 nm. The back faces of two mirrors are anti-reflection (AR) coated at both two wavelengths. A 1 × 2 ×10 mm^3 AR coated PPKTP crystal is placed at the waist of the frequency doubling cavity with 39 μm waist size, and its temperature is precisely controlled at the best phase-matching temperature of 37.5 °C with a measurement precision 0.1 °C. The cavity is locked to the pump laser by using a frequency-modulation PDH sideband technique, in which a high radio frequency (26 MHz) signal is divided into two parts, one is used to drive the elecro-optic modulator (EOM) and the other is multiplied by the detected transmission signal of the cavity using a mixer, the output of which is filtered through a low pass filter and a proportional-integral-derivative (PID) controller. The generated error signal with a high signal-to-noise ratio and a large acquisition range is then used to actively lock the cavity to the pump laser. The output of the cavity consists of the generated blue laser and a small part of infrared pump laser. The two beams are separated by a dichroic beam splitter (DBS). The output infrared laser is detected to generate a reference signal for frequency locking of the cavity. When the cavity is locked, 447.3 nm blue laser is generated by frequency doubling of pump laser operating on $(6^2S_{1/2}, F = 4) \rightarrow (6^2P_{1/2}, F' = 3)$ transition of ^{133}Cs D_1 line at 894.6

nm. All elements of the cavity are mounted on an adjustable rail so that the cavity length can be tuned accurately and steadily, ensuring that a stable output power with 1.6 GHz frequency tuning range at 447.3 nm is achieved as the diode laser frequency is scanned across the $F = 4 \rightarrow F' = 3$ transition of ^{133}Cs D_1 line.

3. Experimental results

The 83 mm long frequency doubling cavity with 39 μm beam waist is designed. In order to satisfy mode matching condition for optimal nonlinear conversion, the beam waist of the input infrared pump light is adjusted via changing the position and focus length of the mode matching lens placed at the front of the cavity. Figure 2 shows the generated blue laser power (black squares) when the cavity length is gradually changed from 77 mm to 84 mm with the mode-matched incident power of 350 mW, while the cavity waist size (blue curve) predicted by ABCD matrix is also shown, a detailed theoretical calculation is shown in [33]. A maximum blue laser power of 178 mW with 350 mW incident infrared laser power is obtained when the cavity length is optimized to be 83 mm, and the corresponding conversion efficiency is 50.8%. Considering 18% wall plug efficiency of TA, the overall efficiency is about 9%.

For getting the high efficiency, the high level of beam quality is also required. Therefore we use a single-mode fiber to spatial filter the beam profile of the laser beam since the tapered amplified diode laser system outputs an elliptical Gaussian beam, which decreases the mode-matching efficiency between the 894.6 nm pump laser and the frequency doubling cavity. A good quality of the laser beam is beneficial for increasing the gain extraction in the nonlinear medium [38]. Converting the elliptical Gaussian profile beam into a nearly circular Gaussian beam leads to an efficient generation of blue laser in a typical circular cross section with transverse Gaussian (or TEM00) mode (see inset of Fig. 3), which can be applied as a pump for efficient down-conversion nonlinear process to prepare a non-classical resource.

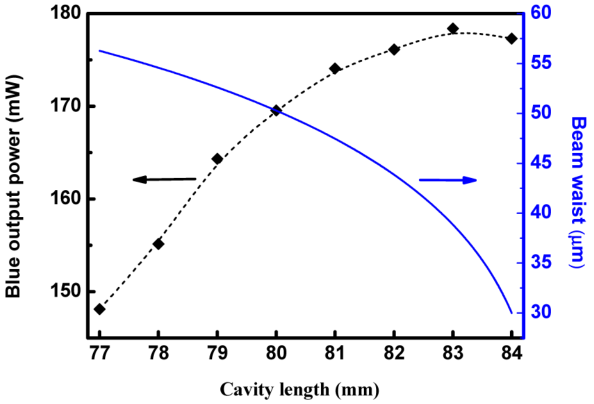

Fig. 2. Blue laser power (black squares) and calculated cavity waist size (blue curve) versus different cavity length with the mode-matched incident pump power of 350 mW.

Figure 3 shows the beam quality M^2 of the generated blue laser source. The measured M^2 values for both axes are $M_x^2 = 1.15$ and $M_y^2 = 1.12$. The transverse intensity distribution for both axes is in good agreement with Gaussian fitting.

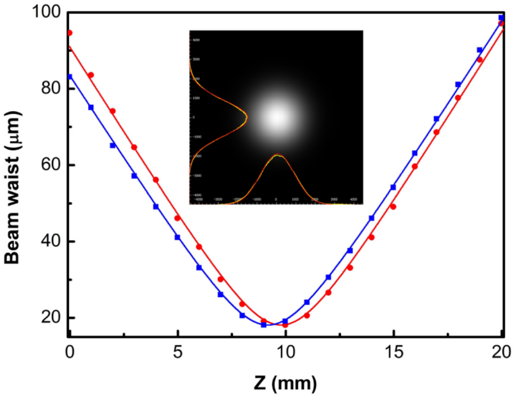

Fig. 3. Beam quality M^2 values of blue laser beam for both axes at maximum incident infrared laser power. The red dots are results for the x axis, and the blue squares for the y axis. The inset is the beam profile of the blue laser.

The frequency tunability of this 447.3 nm blue laser, used as the pump for parametric down conversion, is necessary for preparing the non-classical light exactly matching the transition of ^{133}Cs D_1 line at 894.6 nm. Here, we get the continuous frequency tuning of blue laser via scanning the frequency of the 894.6 nm infrared laser across the $(6^2S_{1/2}, F=4) \rightarrow (6^2P_{1/2}, F'=3)$ transition of Cs D_1 line. Though the frequency of the 894.6 nm infrared laser can be tuned about 15 GHz by modulating the current of the diode laser without mode-hop, a broad scanning range for the generated blue laser is limited by the locking system of the frequency-doubling cavity. As is shown in Fig. 4(a), the generated blue laser can be continuously tuned about 1.6 GHz without losing the lock of the cavity when the infrared laser is tuned 0.8 GHz (black curve), where the power remains stable (green curve). The tunability is also indicated by injecting the blue laser into a confocal F-P cavity with a free spectral range (FSR) of 1.5 GHz and 10 MHz resolution. Figure 4(b), demonstrating smooth tuning of single frequency operation.

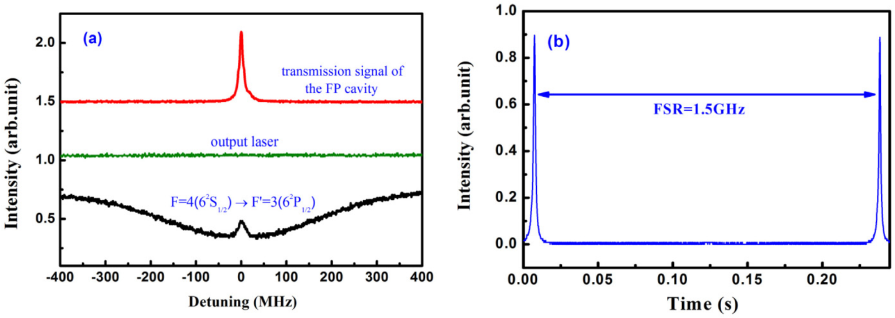

Fig. 4. (a) Saturation absorption spectroscopy (SAS) of $F=4 \rightarrow F'=3$ transition of ^{133}Cs D_1 line (black curve) and blue laser power (green curve) when the infrared diode laser is scanned. (b) The transmission signal of confocal F-P cavity, it is also shown in red curve in (a).

The power stability of the blue laser over 2 hours is shown in Fig. 5 when the infrared laser is locked on the $F=4 \rightarrow F'=3$ transition of Cs D1 line. The RMS fluctuations are 2.3% and 1% at the mode-matched incident power of 350 mW and 200 mW, respectively. Furthermore, we show the intensity noise of 1mW blue laser by a self-homodyne detection including two detectors (S5971, Hamamatsu Photonics), shown in Fig. 6. The subtract and sum photocurrents are amplified via a low-noise amplifier to give the quantum noise limit (QNL) (black curve) and the intensity noise of blue laser source (red curve). It is shown that the intensity noise at low detection frequency (<18 MHz) is higher than the QNL, and it reaches the QNL at frequency above 18 MHz. It should be noted that the peaks in the curves are from the modulation of EOM for PDH locking system.

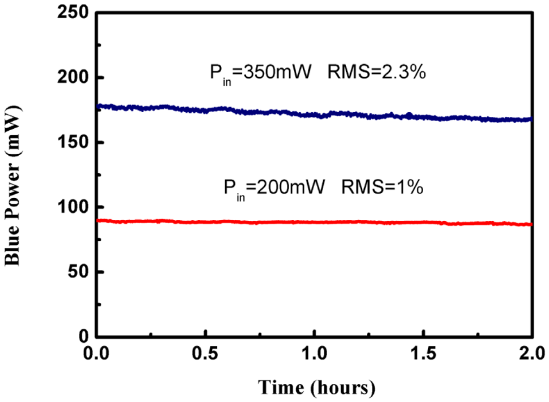

Fig. 5. Power stability of blue laser at different incident power levels over 2 hours.

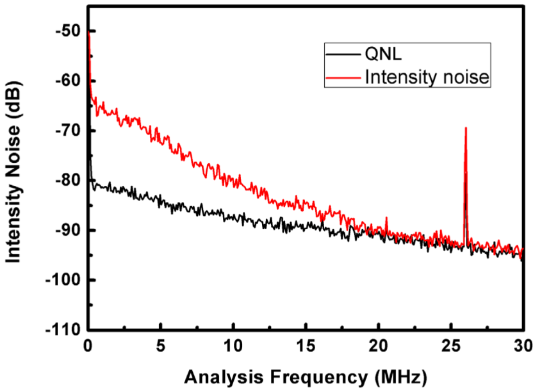

Fig. 6. The measured intensity noise of 1 mW blue laser. The resolution bandwidth and the video bandwidth of the spectrum analyzer are 30 kHz and 1 kHz, respectively.

4.Conclusion

We demonstrate a tunable 447.3 nm blue laser by external-cavity frequency doubling of a ECDL and a TA (boosted) 894.6 nm infrared laser system. A 178 mW blue laser power with 50.8% high conversion efficiency is obtained when the incident infrared power is 350 mW. The blue laser can be continuously tuned over a range around 1.6 GHz without losing the lock of the cavity and has a good beam quality as well as power stability. It can be used to generate 894.6 nm non-classical light which is resonant with the Cs D_1 line for building light-atom interfaces.

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